

Title of the invention**WATER TREATMENT SYSTEM WITH BIOCONTACTOR****5 Cross-reference to related application**

The present application claims priority under 35 U.S.C. § 365(c) to PCT Intl. Appln. No. PCT/CN22/086955, filed on April 15, 2022, which is incorporated herein in its entirety.

Background of the invention

10 Several patents, patent applications and publications are cited in this description in order to more fully describe the state of the art to which this invention pertains. The entire disclosure of each of these patents, patent applications and publications is incorporated by reference herein.

A plurality of microfiltration (MF) and/or ultrafiltration (UF) elements is commonly employed within a pressure vessel. Through the application of pressure to one surface of the membrane, the semi-permeable membrane is able to separate a feed fluid into a treated permeate stream that passes through the
15 membrane and a retentate stream that does not. A common element design comprises a plurality of hollow fiber membranes.

Biological treatment systems have been used for pretreatment of water prior to hyperfiltration. These systems typically remove constituents of water conducive to microbial growth such as nutrients, e.g., organic carbon, nitrate, phosphate, and oxygen, from the water to create an environment in the
20 hyperfiltration modules that is inhospitable to microbial growth. In one design for a multi-element vessel for UF, described in JP10-28847A, an ion exchange layer is incorporated into a pressure vessel containing UF elements, but there is no description of a biological treatment unit. It is desired to provide an improved method of pretreating impure water, especially water to be further purified by hyperfiltration, especially reverse osmosis or nanofiltration.

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Summary of the Invention

The present invention is directed to a water treatment system **2** comprising:

a pressure vessel **10** with a removable lid **12** and a plurality of distinct ports, said distinct ports comprising a feed introduction port **14**, a concentrate removal port **16**, a treated-water removal port **18**, and a cleaning fluid port **20**;

a plurality of vertically aligned separation elements **30** within the vessel **10**, said separation elements **30** each comprising at least one porous membrane **32** selected from the group consisting of a microfiltration membrane and an ultrafiltration membrane; first **34** and second **36** feed fluid passageways that connect the feed-side surface **38** of the membrane **32** to regions outside the element **30**, and a permeate fluid passageway **40** that is in fluid communication with the permeate-side surface **42** of the membrane **32**; wherein at least the first feed fluid passageway **34** is in communication with the concentrate removal port **16** and at least the second feed fluid passageway **36** is in communication with either the feed introduction port **14** or an optional coarse filter **44** that is itself in fluid communication with the feed introduction port **14**;

a permeate collection region **78** within the vessel in fluid communication with the cleaning fluid port **20** and a plurality of permeate fluid passageways **40**;

a biocontactor **50** within the vessel, wherein the biocontactor **50** comprises a plurality of biogrowth surfaces **52** surrounding flow paths **54** through the biocontactor that connect an entry region **56** of the biocontactor **50** to an exit region **58** of the biocontactor **50**, wherein the entry region **56** of the biocontactor **50** is connected to the permeate fluid passageway **40** of multiple separation elements **30** through the permeate collection region **78**, and the exit region **58** is connected to the treated-water removal port **18**; and wherein the flow paths **54** through the biocontactor have a median ratio of surface area to volume which exceeds 15 cm^{-1} , and

a pressure plate **70** containing holes **72** therethrough, wherein the pressure plate **70** separates the vessel into two chambers (**74**, **76**), a first chamber **74** that contains the majority portion **46** of each aligned membrane element **30** and a second chamber **76** that contains the biocontactor **50** and the permeate collection region **78**, wherein said holes **72** enable fluid flow from the permeate fluid

passageways **40** of said membrane elements **30** to the entry region **56** of said biocontactor **50**; and wherein a sealing means **80'** contacting said pressure plate **70** prevents fluid flow between the first chamber **74** and second chamber **76** except through said porous membranes **32**.

- 5 The present invention is further directed to a process of operating the water treatment system **2**, wherein valves **28** are connected to each of the feed introduction port **14**, the concentrate removal port **16**, the treated-water removal port **18**, and the cleaning fluid port **20**; and said valves are alternately positioned to enable operation in a water-treatment mode, in a membrane chemical-cleaning mode, and in a biocontactor cleaning mode; and
- 10 wherein the water-treatment mode is characterized by a treatment flow path that enables sequential convective flow a) through the feed introduction port **14**, b) through the plurality of separation elements **30**, c) through the permeate collection region **78**, d) through the biocontactor **50**, and e) through the treated-water removal port **18**.

The advantages and features of novelty that characterize the invention are pointed out with particularity in the claims annexed hereto and forming a part hereof. For a better understanding of the invention, its advantages, and the objects obtained by its use, however, reference should be made to the drawings which form a further part hereof, and to the accompanying descriptive matter, in which there is illustrated and described one or more preferred embodiments of the invention.

20 **Brief Description of the Drawings**

Figures 1-3 are cross sections of three different embodiments of the water treatment system.

Figures 4a and 4b are partial cutaway views illustrating a removable cartridge before and after loading of particulate media within.

Figure 5 is an exploded view of components within a vessel that are arranged to provide a downward
25 flow of permeate through the biogrowth region of a biocontactor.

Figure 6a and 6b illustrate cross sections of different spiral wound biocontactors, corresponding to embodiments rolled without and with a central tube.

Figure 6c and 6d are perspective views of two embodiments of a spiral wound biocontactor.

Figure 7 illustrates a water treatment system comprising a plurality of parallel vessels and a hyperfiltration system.

Figure 8 is a cross-section of a portion of the biocontactor **50**.

5 Detailed Description of the Invention

The water treatment system includes a pressure vessel that contains both multiple elements in a filtration stage and a biocontactor. A pressure vessel preferably has a cylindrical shape. Preferably the ends of the cylindrical shape are domes of the types commonly encountered in pressure vessels. The biocontactor is suitable to remove easily assimilable nutrients from the water. Preferably, the biocontactor is detachable from the vessel to facilitate replacement. Preferably, resistance to flow within the biocontactor results in a pressure drop across the biocontactor of less than 1 bar (101 kPa), when provided with a flow of 25°C water into the biocontactor at a volumetric rate equivalent to 4 cm/sec times the cross-sectional area of the vessel. Preferably, the biocontactor comprises a spiral-wound flat sheet and spacer material, wherein the flat sheet has two opposing biogrowth surfaces and the spacer material provides flow paths between the biogrowth surfaces, the flow paths extending from the biocontactor entry region to the exit region. Preferably, the biocontactor comprises particulate media that form the biogrowth surface and flow paths are the void between particles. Preferably the particles are resin beads. Preferably, the biocontactor has a horizontal cross-sectional area that exceeds the horizontal cross-sectional area of each separation element by a factor of at least 25. Preferably, the biocontactor has a width of at least one meter, preferably no more than four meters. The term “majority portion” means at least 50% of the total volume, preferably at least 75%.

Referring now to the drawings, wherein like reference numerals designate corresponding structure throughout the views, and referring in particular to Figs. 1-3, multiple embodiments of an inventive water treatment system **2** comprise a pressure vessel **10** with a removable lid **12**. The pressure vessel **10** is preferably cylindrical and vertically oriented. The lid **12** serving to open and close the vessel **10** is preferably on the top of the vessel **10**, although it may also be on the bottom of the vessel **10**. The vessel has several distinct ports. A feed introduction port **14** is connected to a feed line **15** that supplies water to be treated. A concentrate removal port **16** is connected to a concentrate line **17** for discharging untreated liquid. A treated-water removal port **18** is connected to the treated-

water line **19** for supplying treated water to downstream operations. Optionally, a first cleaning fluid line **21'** may be connected to a cleaning fluid port **20**. Preferably, a discharge port **22** near the bottom of the vessel is present for removing settled waste from the vessel. Preferably, one or more air introduction ports **24** connect to air introduction lines **25** to enable air scouring, such as through an air distributor **26**. Preferably, an air removal line **29** connected near an upper accumulation point is used to bleed air from the vessel, such as after a pressure-hold test. In addition, there may be other cleaning fluid lines **21''** in communication with the vessel through valves, for supply and/or discharge of cleaning fluids. Valves **28** external to the vessel may enable a port to serve multiple purposes. For example, in Figure 1, the treated water removal port **18** connects the vessel **10** to the treated water removal line **19** outside the vessel **10**, but the port **18** is also connected to an air removal line **29** and flow therethrough is regulated by its own valve **28'''**.

Within the vessel **10**, there are a plurality of vertically aligned membrane elements **30**, with the membrane elements each comprising at least one porous membrane **32** that is either a microfiltration or an ultrafiltration membrane. Microfiltration membranes have pore sizes that are between 0.2 μm to 10 μm . Ultrafiltration membranes have smaller pores, between about 0.002 μm and 0.2 μm . Most preferred membranes used in this approach have a mean flow pore size between about 0.02 μm and about 0.1 μm . Membranes within each element **30** may be in flat sheet or hollow fiber form, and each has a feed-side surface **38** which contacts the solution to be filtered and a permeate-side surface **42** through which the filtered solution passes. The membrane element **30** also includes a first feed fluid passageway **34** that connects feed-side surfaces **38** of the membranes **32** to the concentrate removal port **16**. The membrane element **30** includes a second feed fluid passageway **36** that connects the feed-side surfaces **38** to either the feed introduction port **14** or to an optional coarse filter **44** that is itself in fluid communication with the feed introduction port **14**. Finally, each membrane element **30** includes a permeate fluid passageway **40** that is in fluid communication with the permeate-side surface **42** of the membrane **32**. In some embodiments, membrane elements **30** may rest on an optional lower support structure **43**, such as a porous plate, horizontal beams, or pedestal. In other embodiments, the position of membrane elements **30** may be maintained by connections with the pressure plate **70**. The portions of first chamber **74** that are on either side of the support structure **43** may be sealed from each other. Preferably, however, the portions of first chamber **74** that are on either side of the support

structure **43** are in fluid communication, as support structure **43** is porous, discontinuous, or otherwise permeable to liquid. Some suitable support structures **43** are described in Intl. Patent Appln. Publ. No. WO2022240460, for example.

There is a biocontactor **50** within the vessel that facilitates controlled growth of a biofilm. The
5 biocontactor **50** may be attached in operation to the vessel lid **12** or to a portion of the vessel **10** below the lid **12**. The biocontactor is preferably detachable from the vessel to facilitate replacement if necessary, and it may be exchanged with a different biocontactor after removal of the lid **12** from the vessel **10**. The biocontactor **50** comprises a plurality of biogrowth surfaces **52** (Figure 6) surrounding
10 flow paths **54** through the biocontactor that connect an entry region **56** of the biocontactor **50** to an exit region **58** of the biocontactor **50**. The flow paths **54** through the biocontactor **50** have a median ratio of surface area to volume which exceeds 15 cm^{-1} , or more preferably even 30 cm^{-1} , or even more preferably 50 cm^{-1} . The resistance to flow within the biocontactor preferably results in a pressure drop
15 across a clean biocontactor at 25°C of less than 1 bar, more preferably less than 0.5 bar, and even more preferably less than 0.2 bar, when provided a water flow rate into the biocontactor **50** equivalent to 4 cm/sec multiplied by the cross sectional area of the vessel **10**. (For example, with a 200 cm diameter cylindrical vessel **10**, the relevant pressure drop across the biocontactor **50** for this purpose would be assessed using a water flow of 31.4 L/sec at 25°C .)

Referring once more to Figs. 1 to 3, pressure plate **70** containing holes **72** separates the pressure vessel **10** into two chambers (**74**, **76**), a first chamber **74** that contains the majority portion **46** of each
20 aligned membrane element **30** and a second chamber **76** that contains the biocontactor **50** and the permeate collection region **78**. Holes **72** in the pressure plate **70** enable fluid flow from the permeate fluid passageways **40** of the membrane elements **30** to the entry region **56** of the biocontactor **50**. A sealing means **80'**, including one or more o-rings or gaskets, for example, contacts the pressure plate **70** and prevents fluid flow between the first chamber **74** and second chamber **76**, except when it passes
25 through the porous membranes **32**.

During production of treated water, permeate flows from the plurality of vertically aligned membrane elements **30** and passes through the biocontactor **50** on its way to the treated-water removal port **18**. A permeate collection region **78** within the second chamber **76** is in fluid communication with the entry

region **56** of the biocontactor, with a plurality of permeate fluid passageways **40**, and with the cleaning fluid port **20**. Hence, the entry region **56** of the biocontactor **50** is connected to the permeate fluid passageway **40** of multiple membrane elements **30** through the permeate collection region **78**. The exit region **58** of the biocontactor is connected to the treated-water removal port **18**.

- 5 In preferred embodiments, the biocontactor **50** is located within the vessel **10** and above the membrane elements **30**. In some embodiments, a majority (by volume) of the biocontactor **50** is laterally surrounded by the removable lid **12**. As shown in Figure 1, the entry region **56** of the biocontactor **50** may be positioned below the exit region **58** of the biocontactor **50**. However, Figures 2 and 3 illustrate embodiments where the exit region **58** is below the entrance entry region **56**. In Figures
- 10 1-3, there are conduits connecting the permeate fluid passageway **40** of membrane elements **30** to the permeate collection region **78**. In Fig. 2, those conduits pass through holes **72** in the pressure plate **70** and extend through the biocontactor **50** to enable an upward flow path that bypasses biogrowth surfaces **52** within the biocontactor **50** and a downward flow path that traverses across the biogrowth surfaces **52**. In Fig. 3, a central conduit connected to the permeate fluid passageways **40** of membrane
- 15 elements **30** also allows for an upward flow path that initially bypasses the biogrowth surfaces **52**. A second sealing means **80''**, including one or more o-rings or gaskets, for example, eliminates a bypass for direct permeate passage between the permeate collection region **78** and the treated-water removal port **18**, forcing permeate from separation elements **30** to flow through the biocontactor **50** and across biogrowth surfaces **52**. One less preferred embodiment that enables a downward flow path that
- 20 traverses across biogrowth surfaces **52** would include a conduit outside the vessel that connects the permeate fluid passageway **40** of elements to a region above the biocontactor **50**. In other embodiments (not shown), the pressure plate may be located below the membrane elements, resulting in a pressurized first chamber being above the lower-pressure second chamber. For instance, permeate may be taken from the lower end of membrane elements, pass through a hole in the pressure plate,
- 25 and then enter the upper end of a biocontactor within the lower chamber. This geometry also enables a generally downward flow through flow paths through the biocontactor, from an upper entry region to lower exit region. One advantage of a downward flow of permeate through biogrowth surfaces **52** is

that bubbles from an air distributor **26** below the biocontactor **50** can be effectively used to detach biofilm from biogrowth surfaces **52** within the biocontactor **50**.

The biocontactor **50** is suitable to treat fluid from multiple membrane elements **30**. Preferably, the cross-sectional area of the biocontactor **50** is at least 10 times greater (more preferably at least 25
5 times greater or at least 50 times greater) than the cross-sectional area of any one membrane element. Preferably, the biocontactor is at least twice as wide as it is tall. Preferably, the ratio of the smallest width of the biocontactor to the height of the biocontactor is more than 2, and preferably more than 4. The biocontactor is preferably less than 0.5 meters tall. For a biocontactor spanning more than one
10 meter in width, support ribs **90** (Figure 4) are preferably positioned on the top and/or bottom to allow the biocontactor **50** to be flushed in both directions while maintaining a differential pressure of at least 1 bar.

Referring to Fig. 8, in one embodiment, the biocontactor **50** comprises particulate media **82** that forms the biogrowth surfaces **52** on which biofilm forms. The flow paths **54** between particles **84** connect an entry region **56** of the biocontactor **50** to an exit region **58** of the biocontactor **50**. In this case, the
15 majority (by volume) of particles **84** within biocontactor preferably have a dimension between 50 microns and 2 mm, more preferably between 200 and 700 microns. Preferably, the particles **84** are spherical resin beads, as these pack well and predictably. The particles may be of more than one type, and a preferred embodiment uses particles of different densities so that layered beds are formed by gravity. In some embodiments, one type of particle sinks in water and one type of particle floats.
20 Screens **86** adjacent the entry region **56** and exit region **58** are sized to prevent passage of these particles.

Preferably, the biocontactor **50** is a removable cartridge **88** that contains a particulate media **82**. Figures 4a and 4b illustrate such a removable cartridge **88**, before and after loading of particulate media **82**. The removable cartridge **88** may include support ribs **90** that strengthen it for both
25 movement and replacement and for operation under pressure. Alternatively, support structures (e.g., ribs or plates) may be built into the vessel structure, including into the lid **12**. In some embodiments, the biocontactor **50** containing particulate media **82** may comprise a plurality of smaller cartridges,

making them easier to move. In a preferred embodiment, the cartridge **88** comprises particulate media **82** that fill not more than 90% of cartridge volume, so that a head space **91** comprises at least 10% of the volume of the cartridge **88** and enables movement of the particulate media **82** in the presence of at least one of water flow or air flow.

- 5 As an alternative to a removable cartridge **88** that contains a particulate media **82**, the media may be removed from the vessel **10** via vacuum suction or as suspended particulates within a liquid flush. Figure 5 shows an exploded view of the top end of a pressure vessel **10** suitable to contain loose particulate media. While the particulate media is not shown in Figure 5, it is intended to be located within the vessel, between the lid **12** and a screen **86**, wherein the screen **86** has hole size suitable to prevent passage of particulate media. To aid in the removing of particles, one or more media ports **92** on the vessel **10** may be connected to a media containment region **94** holding particles within the second chamber **76**. In the embodiment depicted in Figure 5, one media conduit **96'** connected to a media port **92'** is configured to align off-center and directs fluid entering the vessel into a spiraling flow that washes particles from the sides of the media containment region **94**. Optionally, an additional media conduit **96''** and media port **92''** may be located below the majority of media **82** in the media containment region **94**, so that particles are able to flow under gravity from the media containment region **94** upon opening a valve. The two described potential locations of the media ports (**92'**, **92''**) are complementary, so that both may advantageously be present in the vessel **10** for addition and removal of particulates.
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- 15
- 20 When the vessel **10** illustrated in Figure 5 is assembled, the manifold **87**, air distributor **26''**, and screen **86** are fixed at specific locations within the vessel by removable connectors **83** (e.g. screws, magnets, ties, and the like). In the embodiment of Figure 5, spacers **85** are utilized to maintain fixed distances between parts. The figure also shows multiple second sealing means **80''** that force permeate from separation elements **30** to flow through the biocontactor **50** and across biogrowth surfaces **52**, eliminating bypass between the permeate collection region **78** and the treated-water removal port **18**.
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In other embodiments, the biocontactor **50** may be in a spiral wound configuration, as illustrated in Figs. 6a-d. A flat sheet **98** and spacer material **100** may be wound about in a spiral to make a cylindrical

form of similar diameter to the vessel **10**, preferably within 10% of the vessel diameter. The spacer material **100** provides flow paths **54** between adjacent flat sheets **98** to enable fluid flow from the entry region **56** at a first end surface **104** to the exit region **58** at an opposing second end surface **106** of the cylindrical form. Closer spacing of the adjacent flat sheets **98** in the spiral configuration provides a
5 greater number of biogrowth surfaces **52** in the same volume, but at the cost of increased pressure drop and increased difficulty in cleaning. In some cases, winding may be performed about a central rod or tube **102** to facilitate construction. The hollow tube **102** can also provide an alternative path for fluid flow between a first end surface **104** and a second end surface **106** of the spiral wound biocontactor, enabling fluid to avoid in that pass the flow paths **54** adjacent biogrowth surfaces **52**. This can facilitate
10 a change in flow direction through the biocontactor **50**, such as was desired for the vessel configurations of Figures 2, 3, and 5. The outer periphery of each bioreactor **50** is preferably cylindrical and may include an outer shell **108**, as illustrated in Fig. 6c and 6d.

In forming a spiral wound biocontactor, the type of spacer material is not particularly limited. It may be a sheet of extruded net, such as is commonly used for the feed spacer in spiral wound membrane
15 elements. It may be a Tricot knit, as is often used for the permeate spacer in spiral wound elements. It may be dots or lines of adhesive applied to the flat sheet that prevent tight winding. It may be indentations formed in the flat sheet itself, so that adjacent sheets remain separated upon winding. Representative examples of spiral wound membrane elements are described in US8991027, US8142588 and US6881336, for example.

20 Still referring to Figs. 6a-d, the flat sheet **98** to be used in a biocontactor **50** has two opposing biogrowth surfaces **52**, but is not particularly limited. It may be formed from any of several different polymers including polyethylene, polypropylene, nylon, and polyester. It may be non-porous (e.g., impermeable) or porous. (Porous surfaces are preferred, as these can better retain small sections of biofilm despite cleanings, so that re-growth is facilitated. However, for the purpose of calculating
25 surface area to volume, a flat surface is assumed, such that a 0.5 mm distance between adjacent flat sheets corresponds to a 40 cm⁻¹ ratio.)

In a preferred embodiment, the biocontactor **50** is formed using only one continuous flat sheet **98** and adjacent spacer material **100**, as compared to the multiple membrane sheets commonly employed in making spiral wound elements for UF, nanofiltration (NF), and reverse osmosis (RO). Preferred embodiments are depicted in Figs. 6a, 6b, and 6c, for example.

- 5 Preferably, the average distance between adjacent surfaces of wound flat sheet **98** is at least more than, and preferably at least twice, the thickness of the flat sheet. Preferably, the void volume between bio-growth surfaces **52** is at least 50% of the volume of the bioreactor, more preferably at least 65% of the volume of the bioreactor.

- 10 A biocontactor **50** having a spiral wound configuration can telescope under a differential pressure, and the issue is particularly relevant when the diameter (width of biocontactor) is larger than its axial length (height). In some cases, adhesive may be applied intermittently between adjacent sheets, to strengthen the spiral configuration and prevent telescoping under pressure. Support structures (e.g., ribs or plates) may be provided on either or both ends of the spiral wound biocontactor. Figure 6d illustrates ribs **90** on an upper surface of the biocontactor. As depicted, the width (diameter) of the
15 illustrated spiral biocontactor **50** is more than four times the height (in the axial Y direction).

- In the system **2** described herein, the biocontactor **50** receives permeate water from one or more membrane elements **30** within the same vessel **10**. Among other advantages, this arrangement allows the biocontactor to avoid clogging and to have smaller channels and more surface area for biogrowth than if it were directly treating the feed water supplied to the vessel. A large portion of assimilable
20 organic carbon (AOC) can also be removed first in the membrane elements, thereby extending the working range of the biocontactor **50** without cleaning. Similarly, in some embodiments, water from the feed introduction port **14** can be first treated by an optional coarse filter **44** that may be located within or outside of the vessel, downstream or upstream of the port **14**, before allowing the feed to flow into the membrane elements **30**. Preferably, the coarse filter **44** is located within the vessel to
25 make a compact system. Preferably, the coarse filter **44** has a size cut-off (defined as the size for which less than 90% of the particles are retained), which is smaller than the average distance between adjacent biogrowth surfaces **52** in the biocontactor **50**. Removing larger particles prior to membranes

can be particularly advantageous for spiral wound biocontactors, as damaged membranes (e.g., broken fibers) can otherwise allow passage of particles that could clog channels in the biocontactor **50**.

Preferably, as shown in Figure 7, the water treatment system includes a downstream hyperfiltration system **120** comprising at least one pump and a plurality of pressure housings containing reverse osmosis or nanofiltration modules. Preferably, the treated-water removal port **18** is connected to the inlet **122** of a pump **124** supplying treated-water from the biocontactor **50** to a plurality of downstream housings **126** containing hyperfiltration modules **128**. More preferably, multiple similar pressure vessels **10** containing biocontactors **50** are operated in parallel to feed the hyperfiltration system **120**, so that each may be periodically removed from service for cleaning. In this way, the biocontactor **50** and hyperfiltration system **120** may be connected directly, without a buffering storage tank. In some embodiments, a subsequent pressure vessel comprising a phosphate selective resin (not shown) may be located between the biocontactor **50** and the hyperfiltration system **120**.

Referring once more to Fig. 1, it is intended that the biocontactor **50** will be cleaned periodically. Determining appropriate cleaning times for the biocontactor can be best done by measuring the differential pressure drop across the biocontactor **50**, between the entry region **56** and the exit region **58**. With both the biocontactor **50** and membrane elements **30** in series, one or more pressure sensors (**130**, **132**, **136**) that respond to a pressure between the two units is desired. Preferably, a pressure sensor **130** is responsive to pressure in the permeate collection region **78** and (in conjunction with another appropriately positioned sensor **132** within the vessel) is suitable to be used in measuring pressure drop across the biocontactor **50**. Most preferably, a differential pressure sensor **134** is responsive to the pressure in the permeate collection region **78** and a region fluidly connected to the exit region **58**, and the differential pressure sensor **134** is suitable to measure pressure drop across the biocontactor **50**. Hence, either two pressure sensors (**130**, **132**) or one differential pressure sensor **134** may be configured to be suitable to measure pressure drop across the biocontactor **50**. Similarly, it is preferred that one or more pressure sensors (**130**, **136**) are responsive to measure pressure in the permeate collection region **78** and suitable to be used in measuring pressure drop across the membrane elements **30**. Most preferably, a differential pressure sensor **138** is suitable to measure pressure drop across the pressure plate **70**. In practice, a sensor (not shown) placed within a permeate

fluid passageway **40** or within the cleaning fluid port **20** can still be responsive to the pressure in the permeate collection region **78**. In conjunction with a second pressure sensor (**132, 136**) located near the exit region **58** of the biocontactor **50** or in the first chamber **74**, a pressure sensor **130** responsive to the pressure in the permeate collection region **78** would likely be suitable to measure differential

5 pressure across the biocontactor **50** or membrane elements **30**, respectively. One or more pressure sensors installed in nearby locations are suitable to measure pressure drop across the biocontactor **50** or membrane elements **30**, respectively, if their response is directionally the same and if pressure drops between actually compared locations differ by less than 10% from those across the biocontactor **50** or membrane elements **30**.

10 In Figures 1-3, the entry region **56** of the biocontactor is connected to a first cleaning fluid line **21'** through the cleaning fluid port **20**. The exit region **58** of the biocontactor may be connected to a second cleaning fluid line **21''** in addition to the treated water line **19**. Both cleaning fluid lines (**21', 21''**) may be used to enable introduction of cleaning fluids or removal of dislodged particulates. In Fig. 2, the cleaning fluid supplied by the second cleaning fluid line **21''** may be a gas such as air, for

15 example, and the resulting bubbles flow upward from holes **27''** in an air distributor **26''**. Thus, biogrowth is scrubbed from the biogrowth surfaces **52** in the biocontactor **50**. In that case, dislodged material may be removed through a first cleaning fluid line **21'** connected to the entry region **56** of the biocontactor. Fig. 3 illustrates a different approach, wherein a chemical cleaner (for example, without limitation, acid, base, chlorine, or enzymes) may be passed through the biocontactor **50**, which is

20 located between the first cleaning fluid line **21'** and the second cleaning fluid line **21''**. (A valve **28''** selects between the treated-water line **19** and the second cleaning fluid line **21''**.) In this embodiment, the liquid cleaning fluid may be recirculated in multiple passes through the biocontactor **50**, with a recirculation loop (not shown) that includes a recirculation cleaning fluid pump (not shown), the first and second cleaning lines (**21', 21''**), and the biocontactor **50**. The recirculation cleaning fluid pump

25 may also be configured with lines and valves to enable a recirculating flow of liquid cleaning fluid through multiple biocontactors **50** in a plurality of parallel vessels **10**, each having internal parts as described above.

During periods of cleaning the biocontactor **50** or membrane elements **30**, treated water from the vessel **10** is not supplied to downstream operations. Valves and pumps are required to appropriately direct fluids into, out of, and within the vessel **10**, so that undesired contamination is avoided in the membrane elements **30**, the biocontactor **50**, or the downstream hyperfiltration system **120**. For instance, a preferred cleaning method for membrane elements **30** is to distribute chemicals (caustic and/or chlorine, e.g.) into the permeate side **38** of the membranes **32**, perhaps daily, but high levels of these chemicals are generally incompatible with maintaining an active biofilm within the biocontactor **50**. Hence, a preferred embodiment (not shown) would arrange valves to substantially prevent fluid flow of the chemical cleaning solution into the biocontactor **50**. As another example, it is sometimes necessary to remove biofilm from the biocontactor **50**, such as by air scouring or by chemical cleaning. In this mode of operation (not shown), it is important that valves in the system be configured to direct flow to avoid passing the removed biofilm into either the permeate-side **38** of membrane elements **30** or into the hyperfiltration system **120**. Similarly, it can be advantageous to inoculate a recently cleaned biocontactor **50** to support rapid biogrowth, and the inoculant should not pass through the membrane elements **30** or into the hyperfiltration system **120**. In this case, it is preferred that a valve **28'** enable flow through a port **21'** connected to a location between the permeate fluid passageway **40** and the entry region **56** of the biocontactor **50**.

With reference to Figures 1-3, the table below describes several suitable operating conditions for the water treatment system described herein.

Table I.

Production of treated water	The water treatment systems illustrated in Figs. 1, 2, and 3 show connected valves 28 suitable to allow or prevent flow through each of the feed introduction port 14 , the concentrate removal port 16 , the treated-water removal port 18 and the cleaning fluid port 20 . In each case, valves 28 are oriented to illustrate the dominant water-treatment mode, where a continuous flow of feed water enters the vessel 10 through the feed introduction port 14 and exits the vessel as treated water through the treated-water removal port 18 . During this production of
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	treated water, fluid flows in parallel through multiple membrane separation elements 30 and the permeate from these membrane elements 30 is further passed through a biocontactor 50 before it exits the vessel 10. Figures 1 and 3 further illustrate an optional coarse filter 44 located between the feed introduction port 14 and the second feed fluid passageway 36 of each membrane separation element 30.
Forward-flush with chemical-cleaning of membrane elements	Cleaning chemicals are supplied from outside the vessel 10 and caused to flow across the feed-side surface 38 of the membrane 32. In one embodiment, chemicals are introduced by flowing between the feed introduction port 14 and concentrate removal port 16, with the corresponding valves 28 for those ports being open. Permeate is not produced during this chemical cleaning, so the valve 28" between the treated-water removal port 18 and the treated water removal line 19 is preferably closed.
Permeate backflush of membrane elements	During a permeate backflush, water is pushed through the membrane 32 in reverse, from the permeate-side surface 42 of a membrane to the feed-side surface 38 of the membrane. It is not desirable to simply reverse flow within the vessel 10 from the path typically used for producing treated water, since this could force biogrowth from the biocontactor 50 into the permeate-side of membranes. Instead, it is preferred to provide fluid from a port 20 between the permeate collection region 78 and the entry region 56 of the biocontactor 50. More preferably, the valve 28' connected to the cleaning fluid port 20 is open to enable fluid flow into the permeate collection region 78 and through the porous membrane 32.
Chemically enhanced backwash of	Cleaning chemicals are supplied from outside the vessel 10 and caused to flow backwards from the permeate-side surface 42 of membrane to the feed-side surface 38 of the membrane. In this chemical cleaning mode, cleaning chemicals (especially base or chlorine) are preferably introduced by flowing from the

membrane elements	cleaning fluid port 20 , into the permeate collection region 78 , and then further into the permeate fluid passageway 40 of multiple membrane separation elements 30 . A valve 28' connected to the cleaning fluid port 20 is open to enable flow through the cleaning fluid port 20 . Preferably, a valve 28'' connected to the treated-water removal port 18 is closed to prevent flow through that port 18 and through the biocontactor 50 . The cleaning chemicals may be removed through a concentrate removal port 16 .
Air scouring of membranes elements	Another approach to cleaning membranes is air scouring. In this approach air is introduced from below the membrane elements 30 , such as through an air distributor 26 , and foulants are removed via the concentrate removal port 16 . Air is removed through line 29 , as described above. In some cases, air scouring may be performed while flowing through the biocontactor 50 and producing treated water, so the valve 28'' connected to the treated water removal port 18 may optionally be open.
Reversal of flow direction through biocontactor	Biogrowth within the biocontactor 50 is essential for the removal of nutrients; however, biogrowth accumulation will increase pressure drop across this component. Reversing the direction of flow within the biocontactor can encourage removal of biogrowth, but the removed biofilm should not enter the permeate collection region 78 of membrane elements 30 . Accordingly, during the reversal of flow through the biocontactor, a valve 28' connected to the cleaning fluid port 20 is open to enable flow from the vessel 10 through the cleaning fluid port 20 . At the same time, valves 28 connected with the first chamber 74 are preferably closed to inhibit discharge from the biocontactor 50 from entering the permeate collection region 78 and the membrane elements 30 .
Air scouring of biocontactor	Figures 2 and 5 show an air distributor below the biocontactor 50 . If air scouring is used to clean the biocontactor 50 , it is preferred to release discharged waste from the biocontactor to the cleaning fluid port 20 and to a connected cleaning

	fluid line 21' . Release may be done subsequent to the air scouring step but before re-entering the water treatment mode.
Chemical cleaning of biocontactor	The biocontactor cleaning mode may include chemically cleaning the biocontactor, especially with chlorine or caustic. Chemical cleaning can reduce the differential pressure within the biocontactor 50 . In one preferred approach, a valve 28' connected to the cleaning fluid port 20 is open, and a cleaning fluid passes between the entry region 56 and exit region 58 of the biocontactor 50 . Valves 28 connected to ports (14,16) in the first chamber 74 may be closed to prevent chemicals (and biofilm removed from the biocontactor) from entering membranes 32 through the permeate. In an alternative approach the biocontactor 50 and the membrane separation elements 30 may be cleaned at the same time, for example by passing cleaning fluid between the entry region 56 and exit region 58 as described above with at least one valve 28 on and the valve 28' closed. The chemical cleaning of the biocontactor may be shorter or less intense (lower concentration or temperature) than conditions used to clean the membranes.
Inoculation of the biocontactor	Operation of the water-treatment system 2 may include a step of inoculating the biocontactor 50 with a bacteria laden solution. This can have particular advantage subsequent to installing a new biocontactor, subsequent to re-installing a removed and cleaned biocontactor, or subsequent to chemically cleaning a biocontactor within the vessel 10 . In a preferred embodiment, the bacteria laden solution contains bacteria previously removed from a biocontactor, especially via air scouring or reversal of flow within the biocontactor. While inoculation is not itself a cleaning step, it can reduce the time to return to efficient operation after a biocontactor cleaning mode that uses caustic or chlorine. In preferred embodiments, the bacteria laden solution is introduced to the biocontactor through the permeate collection region 78 . It is further preferred

	that the bacteria laden solution flows into the permeate collection region 78 through the cleaning fluid port 20 .
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During operation of the water-treatment system, valves are most commonly positioned to enable a water-treatment mode. Referring to Fig. 1, in this mode, a valve **28'** connected to the cleaning fluid port **20** is closed to prevent flow through the cleaning fluid port **20**, and other valves **28** are positioned
5 to create a treatment flow path that enables sequential convective flow:

- a) through the feed introduction port **14**,
- b) optionally through a coarse filter **44**,
- c) through a plurality of separation elements **30**, passing in each case through the second feed fluid passageway **36**, through at least one porous membrane **32**, and
10 through a permeate fluid passageway **40**,
- d) through the permeate collection region **78**,
- e) through the biocontactor **50**, passing in each case across biogrowth surfaces **52** from an entry region **56** to an exit region **58**,
- f) and through the treated-water removal port **18**.

15 In a preferred embodiment, for example as depicted in Fig. 3, fluid flows across the biogrowth surfaces **52** of the biocontactor **50** in a generally downward flow path during this water-treatment mode.

Referring once more to Figs. 1, 2, and 3, operation further includes a membrane chemical-cleaning mode wherein valves are positioned to enable flow of a cleaning fluid containing chlorine or caustic, for
20 example, through the membrane separation elements **30** and to restrict flow of the cleaning fluid through the biocontactor **50**. In this mode, a valve **28'** connected to the cleaning fluid port **20** is preferably opened to enable flow through the cleaning fluid port **20** and into the permeate fluid

passageway **40**, and a valve **28''** connected to the treated-water removal port **18** is preferably closed to prevent flow through that port **18** and through the biocontactor **50**.

Still referring to Figs. 1, 2, and 3, operation further includes a biocontactor cleaning mode, wherein valves are positioned to enable a cleaning fluid to flow through the biocontactor **50**. In the

5 biocontactor cleaning mode, particles dislodged from the biocontactor **50** are prevented from entering the membrane separation elements **30**. In a preferred embodiment depicted in Fig. 7, treated-water from the biocontactor **50** is supplied to downstream hyperfiltration modules **128** during the water-treatment mode and flow that passes through the biocontactor **50** is prevented from flowing to the hyperfiltration modules **128** during the biocontactor cleaning mode. Figure 7 illustrates valves (**140'**,
10 **140''**) that may be positioned to isolate the biocontactor being cleaned. In the central position, valves (**140'**) are positioned so that a pump **144** and recirculation loop **142** directs fluid through the biocontactor. In one embodiment, the cleaning fluid passing through the biocontactor **50** contains chlorine or caustic. In another embodiment, the cleaning fluid passing through the biocontactor **50** comprises air or other gas bubbles. In a preferred embodiment, the direction of fluid flow through the
15 biocontactor **50** is opposite during the water-treatment mode and the bioreactor cleaning mode.

In some preferred embodiments, the biocontactor **50** is periodically cleaned by air scouring. As illustrated in Fig. 2, separate air distributors (**26'**, **26''**) with holes (**27'**, **27''**) may be present below both the membrane elements **30** and the biocontactor **50**. Air introduction lines (**25'**, **25''**) are shown connected to individual air introduction ports (**24'**, **24''**) and to the air distributors (**26'**, **26''**).

20 Preferably, a common source of pressurized gas supplies the air introduction lines (**25'**, **25''**) associated with air distributors (**26'**, **26''**) below the membrane elements **30** and the biocontactor **50**. The air or other gas may be released through air removal line **29**.

In some preferred embodiments, the biocontactor **50** is periodically cleaned by passing a cleaning fluid through it, where the cleaning fluid is preferably chlorine (e.g., sodium hypochlorite or other
25 hypochlorites) or caustic (hydroxide salts, preferably sodium hydroxide or potassium hydroxide). In some preferred embodiments, a common cleaning fluid port **20** is used to provide chemicals that are used in both cleaning the membrane elements **30** and cleaning the biocontactor **50**. In Fig 7, valves (**140'**, **140''**) are shown positioned to enable the middle biocontactor to be taken off-line for cleaning

while continuing operation of others. The liquid cleaning fluid may be recirculated in multiple passes through the biocontactor **50**, with a recirculation loop **142** that includes a recirculation cleaning fluid pump **144**.

While certain of the preferred embodiments of the present invention have been described and
5 specifically exemplified above, it is not intended that the invention be limited to such embodiments.
Rather, it is to be understood that even though numerous characteristics and advantages of the present
invention have been set forth in the foregoing description, together with details of the structure and
function of the invention, the disclosure is illustrative only, and changes may be made in detail,
especially in matters of shape, size and arrangement of parts within the principles of the invention to
10 the full extent indicated by the broad general meaning of the terms in which the appended claims are
expressed.

Claims

1. A water treatment system **2** comprising:

a pressure vessel **10** with a removable lid **12** and a plurality of distinct ports, said distinct ports comprising a feed introduction port **14**, a concentrate removal port **16**, a treated-water removal port **18**, and a cleaning fluid port **20**;

a plurality of vertically aligned separation elements **30** within the vessel **10**, said separation elements **30** each comprising at least one porous membrane **32** selected from the group consisting of a microfiltration membrane and an ultrafiltration membrane; first **34** and second **36** feed fluid passageways that connect the feed-side surface **38** of the membrane **32** to regions that are within the vessel **10** and outside the element **30**, and a permeate fluid passageway **40** that is in fluid communication with the permeate-side surface **42** of the membrane **32**; wherein at least the first feed fluid passageway **34** is in communication with the concentrate removal port **16** and at least the second feed fluid passageway **36** is in communication with the feed introduction port **14**;

a permeate collection region **78** within the vessel in fluid communication with the cleaning fluid port **20** and a plurality of permeate fluid passageways **40**;

a biocontactor **50** within the vessel, wherein the biocontactor **50** comprises a plurality of biogrowth surfaces **52** surrounding flow paths **54** through the biocontactor that connect an entry region **56** of the biocontactor **50** to an exit region **58** of the biocontactor **50**, wherein the entry region **56** of the biocontactor **50** is connected to the permeate fluid passageway **40** of multiple separation elements **30** through the permeate collection region **78**, and the exit region **58** is connected to the treated-water removal port **18**; and wherein the flow paths **54** through the biocontactor have a median ratio of surface area to volume which exceeds 15 cm^{-1} , and

a pressure plate **70** containing holes **72** therethrough, wherein the pressure plate **70** separates the vessel into two chambers (**74**, **76**), a first chamber **74** that contains the majority portion **46** of each aligned membrane element **30** and a second chamber **76** that contains the biocontactor **50** and the permeate collection region **78**, wherein said holes **72** enable fluid flow from the

permeate fluid passageways **40** of said membrane elements **30** to the entry region **56** of said biocontactor **50**; and wherein a sealing means **80'** contacting said pressure plate **70** prevents fluid flow between the first chamber **74** and second chamber **76** except through said porous membranes **32**.

- 5 2. The water treatment system of claim 1, wherein the biocontactor **50** is detachable from the vessel **10** and may be exchanged with a different biocontactor after removal of the lid **12** from the vessel **10**.
3. The water treatment system of claim 1, wherein the resistance to flow within the biocontactor **50** results in a pressure drop of less than 1 bar, when provided a flow of 25°C
10 water into the biocontactor **50** at a volumetric rate equivalent to 4 cm/sec multiplied by the cross-sectional area of the vessel **10**.
4. The water treatment system of claim 1 further comprising a pressure sensor responsive to pressure in the permeate collection region **78** and configured in the vessel to be used in measuring pressure drop across the biocontactor **50**.
- 15 5. The water treatment system of claim 1 wherein the biocontactor **50** is in a spiral wound configuration formed of multiple windings of a flat sheet **98** and spacer material **100**; wherein the flat sheet **98** has two opposing bio-growth surfaces **52** and the spacer material **100** provides flow paths **54** between the biogrowth surfaces **52**, extending from the entry region **56** to the exit region **58**.
- 20 6. The water treatment system of claim 1 wherein the biocontactor **50** comprises particulate media **82** that form the biogrowth surfaces **52** and flow paths **54** between particles **84**.
7. The water treatment system of claim 6, wherein the particulate media **82** is contained within a removable cartridge **88**.
8. The water treatment system of claim 1, wherein the biocontactor **50** has a horizontal cross-
25 sectional area that exceeds the horizontal cross-sectional area of each separation element by a factor of at least 25.

9. The water treatment system of claim 1, wherein the biocontactor **50** is more than a meter in width and has support ribs **90** on the top or bottom surface that allow it to be flushed in both directions while maintaining a differential pressure of at least 1 bar.
10. A process of operating the water treatment system of claim 1, wherein valves **28** are connected to each of the feed introduction port **14**, the concentrate removal port **16**, the treated-water removal port **18**, and the cleaning fluid port **20**; and said valves **28** may be positioned to enable operation in a water-treatment mode, in a membrane chemical-cleaning mode, and in a biocontactor cleaning mode; and
- 10 wherein the water-treatment mode is characterized by a treatment flow path that enables sequential convective flow a) through the feed introduction port **14**, b) through the plurality of separation elements **30**, c) through the permeate collection region **78**, d) through the biocontactor **50**, and e) through the treated-water removal port **18**.
11. The process of claim 10 wherein the biocontactor cleaning mode is practiced with valves **28** positioned to provide a flow of air or liquid through the biocontactor **50** to dislodge particulates, and to prevent the discharged particulates from contacting membranes **32**.
12. The process of claim 11 wherein the liquid is a cleaning fluid comprising a chemical selected from chlorine and caustic, and the membrane chemical-cleaning mode is practiced with valves **28** positioned to prevent flow of the cleaning fluid through the biocontactor **50**, and to enable flow of cleaning fluid either
- 20 a) across the feed-side surface **38** of the membrane **32**, between first **34** and second **36** feed fluid passageways, or
- b) through the membrane **32** from the permeate-side surface **42** to the feed-side surface **38**.
13. The process of claim 12 wherein the biocontactor cleaning mode employs a flow of cleaning chemicals through the cleaning fluid port **20**.
- 25 14. The process of claim 12, wherein the water-treatment mode includes a flow path that traverses across the biogrowth surfaces **52** in a downward direction.

15. The water treatment system of claim 1, wherein the feed introduction port **14** is equipped with a coarse filter **44** that prevents particles in the feed from entering the interior of the vessel **10**.